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ON THE RELATION OF ION AND ELECTRON EMISSION TO DIODE DIAGNOSTICS

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Abstract

The detailed understanding of the mechanisms governing the performance of a thermionic converter is confused by the interactions between the electrodes and the plasma in the interelectrode space. A guard-ring variable-spacing diode capable of spacings as small as 8μ has been used to minimize the electron and the ion transport effects in the plasma. Relations have been established that satisfactorily interrelate electron and ion emissions of a oriented tungsten emitter over a broad range of emitter temperatures and cesium pressures. An electron work function determined from saturation currents and the use of the Richardson Dushman emission equation is in general agreement with empirical extrapolations of the early Langmuir-Taylor low-pressure cesium experiments.

Work functions based on observed ion currents were determined by the use of the Langmuir-Saha equation. A field effect was noted and was adequately treated by the application of the Schottky mirror-image theory. The work functions determined from ion currents are generally 0.07 ev higher than those obtained by electron emission.

The electron and the ion-emission properties yield information on the surface potentials existing in the plasma. This information coupled with an energy balance of the converter indicates that the anomalously high currents observed during the ignited mode of operation can be described in terms of a large ion current from the plasma space that in turn "pumps" atoms to the emitter surface. The ion-atom charge-exchange process is the assumed mechanism that alters the particle arrival rates. The upper limit of the particle arrival rates is postulated to be about two times the normal atom arrival rate except in the case of very high ion currents.

Author

Introduction

It is well known that thermionic converter performance is strongly dependent on the work functions of the emitter and the collector. The early work of Langmuir and Taylor[1] has been used as a guide for the work function of the tungsten-cesium system. The application to a thermionic converter involved extrapolations of Langmuir's data by about five orders of magnitude in terms of cesium arrival rates. More recently Houston[2] obtained data at cesium pressures closer to the operating conditions of thermionic converters by the emission probe technique. The data obtained in actual thermionic converters are in what might be called casual agreement with the extrapolated data of Langmuir and Houston. However, the apparent saturation currents (related to emitter work function) and retarding potential characteristics (related to collector work functions) depart from the extrapolated data of references 1 and 2 very significantly as the cesium pressure in the interelectrode space exceeds a value of 0.1 torr, or as the space between the electrodes approaches 50μ or more. The objective of this work was to relate the more basic experiments of references 1 and 2 to data obtained in an actual thermionic converter.

The use of a thermionic converter for obtaining information of this type necessarily required special design features and also involved a determination of the influence of ion-production probability, space-charge effects, electron scattering, and ignited modes on the apparent work functions. The interrelated effects of all factors affecting work functions are complex and, therefore, in view of the limited space available, will be treated somewhat superficially. The following will be considered: emitter work function of a cesiated oriented tungsten emitter determined by measurements of saturated electron and ion currents; work function of a cesiated polycrystalline collector by the use of a retarding potential method; illustrations of the effect of scattering on apparent collector work function; and finally an explanation of the "ignited" mode of operation of a thermionic converter and the consequent effect on apparent emitter work functions.

Apparatus and Procedure

The primary features of the thermionic converter are shown in Fig. 1. The converter is in the form of a planar diode with a demountable emitter and collector. The 1.5-cm diameter, 3-cm-long emitter structure was formed from a tungsten crystal oriented to expose the 110 (Miller index) plane. Most of the surface was a single crystal; however, a few subcrystals existed. The maximum misorientation from the 110 plane was about $1\frac{1}{2}^{\circ}$.

The emitter guard was flush with the emitter. The radial clearance was about 3 mils at operating temperatures. The radial clearance was kept symmetrical by three equally spaced tungsten pins that were in mechanical contact with the emitter and its guard but were electrically isolated by an alumina spacer. External electrical contact of the emitter guard was provided by a copper diaphragm that was brazed into the diode body. The copper diaphragm was also used to cool the emitter guard.

The collector and support were formed from polycrystalline tungsten. The collector assembly was movable and was attached to the main diode body through the use of a stainless-steel bellows. Three equally spaced differential screws were used to adjust and to measure the spacing.

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The collector guard radial clearance was 3 mils, and the guard position was fixed and was about 20 mils from the emitter surface. Radial clearance was maintained by relative adjustments of the differential screws. The design of the electrical and thermal aspects of the collector guard was similar to that of the emitter guard.

The cesium reservoir was located in a massive copper cylinder that was connected to the diode by a 5/16-in. copper tube.

The emitter was heated by the electron-bombardment heater shown in Fig. 2. The electrodes of the heater were shaped to vary the intensity of the electron beam in order to compensate for the large radiation and conduction losses present in the edge of the planar diode design. The final design of the filament and electron deflector that gave the most uniform temperature also provided a view of the back surface of the emitter. Temperature stability of the emitter was established by the use of a properly matched external load.

The emitter guard, collector, collector guard, insulator, flange, and cesium-reservoir temperatures were established by inserting the diode in a gas-filled oven. Helium or nitrogen gas was used in the oven. Local resistance heaters and gas jets at or near the above diode elements were sometimes used to maintain temperature control.

The emitter temperature was determined by an optical pyrometer that viewed the back surface of the emitter through a shuttered window and prism (Fig. 2). The problem of spurious radiation was avoided by the aforementioned electron-bombardment heater design. The relationship between surface temperature and back-surface temperature was established by a series of tests in a dummy diode that provided for a simultaneous view of a blackbody hole in the front surface and the back surface. The characteristics of the electron-bombardment heater and pyrometer provided a useful emitter temperature range of 1350° to 2000° K.

The cesium-reservoir temperature was measured by a thermocouple in conjunction with a high gain amplifier and digital voltmeter. All other temperatures, emitter flange, collector assembly, and insulators were measured by thermocouples with the output displayed by a digital voltmeter.

The diode bias voltage was provided by a power transistor assembly. The voltage supply was divided into two sections, a high-current section that normally operated from -4 to +12 v and a low-current section that normally operated for voltages from 0 to -40 v. The high-current section was used for electron currents, while the low-current section was for the ion currents. Voltages in the high retarding range were controlled manually. A data sampling procedure was employed at conditions of high current to avoid either severe electron cooling or plasma heating of the emitter. The primary data were recorded by a pen-type X-Y recorder whose maximum writing speed was about 15 in./sec. The logarithm of current density as a function of dimensionless volts (volts divided by electron volt equivalence of temperature, qV/kT) was recorded directly in most of the runs. Appropriate shunt selections yielded useful current information over about eight orders of magnitude. The measured current did not include collector-guard current, since the guard was connected to the system past the current measuring shunts. The collector guard was essentially at collector potential for all low-current determinations and was allowed to float at high-current conditions.

Emitter Work-Function Determinations

Electron saturation current was measured by operating the diode at spacings on the order of 3 to 11μ (nominally 8μ) in order to minimize space charge and electron scattering effects. Typical current-voltage curves obtained by this technique appear in reference 3. The saturation currents were usually clearly defined in the ion rich region, that is, where the ion current produced by surface ionization is in excess of the current required for neutralization of charge density. In other words,

$$J_i > J_e \sqrt{\frac{m_e}{m_i}} \tag{1}$$

where J is the current density and m is the mass. The subscripts e and i refer to electron and ion, respectively.

The emitter work function was then calculated from the following Richardson-Dushman equation

$$\varphi_1 = \frac{kT_1}{q} \ln\left(\frac{120.1\ T_1^2}{J_s}\right) \tag{2}$$

where φ is the work function, k is the Boltzmann constant, T is the temperature, q is the unit charge, and J_s is the saturation current density. The subscript 1 refers to the emitter. The saturation current was not clearly defined in the electron rich condition or at conditions where the current-voltage curves were confused by arc or ignited modes of operation. The technique used in identifying emitter work functions under the ignited mode will be discussed in a later section.

The work function could be estimated in the electron rich region, despite the lack of adequate ions for space charge utilization, by applying an accelerating voltage sufficient to produce an apparent saturation current. The use of space-charge analysis, such as presented by Goldstein[4] or Nottingham,[5] assisted in the definition of saturation currents. Collisional and plasma interactions sometimes confuse the direct reduction of the data, so an additional check of the emitter work function was obtained by the application of the Saha-Langmuir equation to the saturated ion currents.

The measurements of ion currents involved several experimental difficulties. The probability of ion formation is low in the electron rich region; therefore, currents were often in the microampere range. The cesium-covered insulators in the converter could allow the small ion currents to be lost in leakage currents. The guard rings previously discussed minimized the problem. Difficulties in the ion rich region existed because the large mass of the cesium ion induced a severe space charge. High retarding potentials on the order of 45 v were employed to compensate for the ion space-charge effect. However, this in turn produced a significant Schottky alteration of the emitter work function. The effect of the Schottky enhancement of ion-production probability and the techniques used in reducing the data of this research vehicle are described by Nottingham.[6] The application of the emitter work-function determination by ion-current measurements was based on the correlation of the work function determined by the observed ion current (corrected for the Schottky field effect) to that calculated by the following modified Saha-Langmuir equation:

$$\varphi_1 = \frac{kT}{q}\left(\ln \frac{2\nu_{i,0}}{\nu' - \nu_{i,0}}\right) + 3.893 \tag{3}$$

where ν is the particle flux, ν' refers to the total particle arrival rate, and the subscript i,0 refers to the zero-field ion current.

The emitter work functions of the oriented (110) tungsten emitter measured in the closed space converter are compared in Fig. 3 to the values predicted by Nottingham[6] on the basis of data given by Taylor and Langmuir[1] and Houston.[2] Close agreement exists over a range of cesium temperatures from 360° to 565° K, which corresponds to a pressure of 2×10^{-4} to $1\frac{1}{2}$ torr, respectively, and emitter temperatures from 1350° to 1900° K. The interelectrode spacing used in this range of pressures corresponded to about 1 mean free path or less for an electron-cesium neutral collision. The close agreement between the results in the diode and the extrapolated data of Taylor and Langmuir and Houston indicated that the results in the basic experiments can be applied directly to a thermionic converter environment. The results suggest that the tungsten substrate exhibits a similar cesium adsorption characteristic. Some confusion exists as to what the actual work function of the tungsten substrate was in the various experiments. Taylor and Langmuir heat treated their wires extensively and presumed that the surface was predominantly 110 tungsten. Houston, on the other hand, does not believe that the wires used in his emission experiments were necessarily that of the 110 plane.[7] The agreement of the three experiments may be explained in the rather rapid annealing and adjusting of the surface of the emitter that occurs at temperatures greater than 1760° K in a cesium atmosphere as described in the discussion of the cathode effect in reference 3.

The ion-current determination of the work function consistently gave values that were approximately 0.07 ev higher than those obtained by electron emission. The departure could conceivably be due to variations in emitter temperature, variations in emitter work function, or errors in temperature and current measurements. Each of the possibilities were explored, and no self-consistent explanation could be established. It is interesting to note that the ion-production probability expression neglecting electron spin (in the expression for ion production) matches experimental data more closely than the standard Saha-Langmuir expression. This fact has been noted by Nottingham[6] for he shows that the data obtained by the converter used departs from the classical expression in the same manner as the experimental results of Copley and Phipps.[8]

Collector Work Function

The collector work function was measured by the usual retarding potential technique using the following expression:

$$\varphi_{2_{\text{apparent}}} = \left[\frac{kT}{q} \ln\left(\frac{120.1\ T_1^2}{J_R}\right) - V_o\right] \tag{4}$$

where φ_2 is the collector work function, J_R is the current determined on the retarding portion of a current voltage curve corrected for ion-current, back emissions, and space charge effects, and V_o is the applied potential.

The problems encountered in the measurement of collector work function were those related to leakage currents, ion currents, electron and ion space charge, electron back emission, and electron scattering.

The leakage current was minimized by setting the Fermi level of the collector and its guard at essentially the same potential. Ion saturation currents were measured at the same conditions as the electron-current measurements. If the ion currents were significant, the electron current was adjusted through the use of space-charge relationships. The results of space-charge solutions involving simultaneous electron-ion emission (as treated in ref. 4) were used as a guide in reducing the net-current curves. The simple extrapolation of ion current often applied in adjusting net currents of probe and converter studies was not used. Electron back emission was determined directly and corrections were made by measuring the current in the high retarding region. The ion-current portion could be identified by cooling the collector to the point where electron back emission was trivial. The effect of electron scattering was evaluated by making a series of measurements at various spacings encompassing the range from less than 1 mean free path to about 80 mean free paths (based on electron neutral scattering with a collision probability, P_c, of 1400).

The effect of interelectrode spacing on apparent collector work function is given in Fig. 4. The work function for the smallest spacing is about 1.72 ev at a collector temperature of 743° K. The apparent work function increases about 0.15 to 0.20 v as the spacing increases from that of less than 1 mean free path to 80 mean free paths. It is suggested that this change is due to the increased probability of electron back scattering with increased spacing.

The effect of collector temperature on collector work function is shown in Fig. 5. The low-temperature condition corresponds to the condition where multiple layers of cesium should be present on the collector. The value in Fig. 5, when adjusted for spacing, is in agreement with the literature value for bulk cesium. The minimum value of about 1.68 ev, if again adjusted for spacing, is about 0.04 ev lower than the value extrapolated from Taylor and Langmuir.[1]

Observations in the Ignited Mode

Thermionic converters consistently exhibit current densities greater than those predicted by the extrapolation of the Langmuir-Taylor data. It has been suggested by many investigators that the increase is related to an increased arrival rate resulting from the ion currents flowing from the plasma to the emitter coupled with a Schottky depression of emitter work function caused by an ion rich sheath at the emitter.

The variable spacing feature of the research diode, which was so useful in the passive mode studies of work function, was applied to studies of the ignited mode. An example of a typical current-voltage curve is shown in Fig. 6. The passive mode is that portion of a curve characterized by an initial Boltzmann line followed by electron space-charge behavior. At a current density of about 1 amp/sq cm the converter "ignites" and a higher current density and new mode of performance are exhibited. This ignited mode is stable from the intercept on the passive-mode region up to the

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maximum current observed. At the intercept on the passive mode the converter "de-ignites" and again follows the usual Boltzmann and space-charge relationships. The nature of the current-voltage behavior in the "ignited" mode near the knee of the curve indicates the existence of an electron space charge and thus a double sheath condition. The space-charge behavior suggests that Schottky enhancement of electron emission is not too probable.

An energy balance of the converter was established in an attempt to quantitatively assess the features of the ignited mode. The method used is essentially that used in plasma discharge research, and the method more recently adapted to thermionic converters by Houston.[9] The application of the energy-balance technique is somewhat limited due to extraneous losses present in a planar diode. The technique used to circumvent some of the problems is as follows. Point A is established in the passive mode and then point B is determined at the location where the input power and emitter temperature are the same as observed at point A (Fig. 6). Even though nonassessable losses exist in the planar configuration used, the comparable losses at points A and B are largely cancelled. Thus an energy balance can be established between the two operating conditions. The energy-balance relationship used is indicated in Fig. 6. A more general form of the resultant expression that treats the case when electron cooling at point A is not negligible is given as

$$\dot{Q}_{\substack{\text{Electron}\\\text{cooling at}\\\text{point B}}} - \dot{Q}_{\substack{\text{Electron}\\\text{cooling at}\\\text{point A}}} = \dot{Q}_{\substack{\text{Plasma}\\\text{heating at}\\\text{point B}}} + \left(\begin{array}{l}\text{Difference in gaseous}\\\text{conduction at points}\\\text{A and B}\end{array}\right) \tag{5}$$

where $\dot{Q}$ represents an energy flux. It can be seen from Eq. (5) and the corresponding equation in Fig. 6 that use is made of the knowledge of the energy involved in the transport mechanisms in the passive mode of operation. If it is assumed that at point B the plasma heating is primarily that of ions arriving at the emitter from the plasma, an approximation of the ion current can be established in terms of equating the total energy of all the arriving ions to the energy of all of the emitted electrons.

The energy of the arriving ion is illustrated in Fig. 7. The model shown is equivalent to that of surface recombination of an ion and is presented in the alternate form shown for ease in identifying the various energy terms. The steps are now given. First, an ion moves from a region near the surface potential of the collector to the surface potential of the emitter. The energy of the ion relative to the surface is $q(V_p \pm \Delta V)$ where ΔV represents the uncertainties of the point of origin of the ion in the plasma space, and V_p is the potential variation shown in Fig. 7. Second, an electron is moved from the Fermi level of the emitter to the surface potential which requires an energy of $q\varphi_1$. Third, the particles recombine to form an atom liberating the ionization energy of 3.893 ev (it can be assumed the particles recombine in a volume adjacent to the surface and then transfer their energy to the surface as they are adsorbed as an atom, or it can be assumed that recombination occurs on the surface). Fourth, the particle is reemitted as an atom for the cases considered since φ_1 is less than V_i, the ionization potential. The energy balance shown neglects the translational temperatures of the ion, electron, and atoms. This approximation is used since translational energy is small in comparison to the other energies involved, and also, the translational terms appear in the numerator and the denominator and therefore tend to cancel. It is assumed that the energy state of the ion in the plasma can be determined within ±0.8 v, and it is further assumed that the variation in the normal gaseous thermal conduction can be neglected as a first approximation. On the basis of these assumptions, the final energy-balance relation used in predicting the ion current should be within about ±15 percent of a more exact formulation. Houston[9] arrives at a similar conclusion in his treatment of a cylindrical diode. Typical current-voltage curves are shown in Fig. 8 in which the heat balance point in the ignited mode is determined at four interelectrode spacings. The accelerating voltages observed at the balance point decrease as spacing increases. The application of an accelerating potential of about $1\frac{1}{2}$ v at a spacing of 567μ is sufficient to permit the plasma heating of the emitter to compensate exactly for the electron cooling. It is interesting to note that the apparent saturation current (observed for the smallest spacing in the passive mode portion of the curve) corresponds to a value of saturation current predicted from the extrapolated data of Langmuir and Taylor. Current densities considerably higher than those predicted by the extrapolated values[6] are experienced in the ignited mode.

The application of the relationship used in estimating the ion current at the balanced inlet power - temperature condition is shown in Fig. 9. The current density is presented as a function of interelectrode spacing at emitter temperatures of 1700° and 1800° K. The cesium-reservoir temperature is 565° K. The ion current calculated on the basis of the approximate relationship is shown by the shaded lines. It has been shown previously that an agreement exists between the work functions (therefore emission currents) observed in these tests and the extrapolated data of Langmuir.

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It follows that the emission currents can be related to particle arrival rates. An electron-emission current density has been predicted by calculating a new particle arrival rate that consists of the normal atom arrival rate and the estimated ion current. If the simple model of an enhanced arrival rate on the basis of ion current is to be valid, the sum of the predicted electron current and calculated ion currents should match the observed net current. As can be seen in Fig. 9, the agreement is quite poor, particularly at the conditions of lower emitter temperatures. Thus, this simple explanation of net current in the ignited mode is unsatisfactory.

It was noted that the estimated ion current at the balance point was quite high amounting to 3 to 5 amp/sq cm. The ion current in itself constitutes a reasonable fraction of the total possible particle arrival rate at the surface of the emitter since the atom arrival rate expressed in current-density terms would amount to 18 to 25 amp of atom flux. The flux rate is dependent on spacing the larger values corresponding to the Knudsen or rarefied gas-particle flux; the lower value corresponds to that calculated on the basis of continuum flow that exists at the largest spacings. The relatively large ion current and the very high probability of a charge exchange collision between the ion and the cesium atom[10,11] suggest that there is a high probability of transferring the directed motion of the ion current to that of the atoms. The difference in the surface potential and plasma potential produces a strong accelerating field for ions. The field in turn causes the ions to be directed toward the emitter at a significant velocity. The transfer of velocity to the atoms, which may occur in several steps because of the high collision probability, will increase the total particle arrival rate considerably. An upper limit to the particle arrival rate by the charge-exchange mechanism is postulated to exist. This upper limit exists because a large fraction of random velocity components perpendicular to the directed motion should be maintained in a charge exchange collision. The retention of the perpendicular velocity distribution will in effect keep the particle concentration equivalent to that of the gas surrounding the inner electrode space. But the particle concentration will tend to be redistributed into two groups - the high velocity particles moving toward the emitter and the particles that have contacted the emitter, have become thermalized, and are emitted at a translational velocity equivalent to that of the emitter temperature. The velocity differences cause a shift in particle concentration of the two groups. The high-velocity group approaches zero concentration and the low-velocity group approaches twice the normal concentration. The particle arrival rate at the emitter surface under these conditions will therefore approach a value of two times the normal arrival rate as the velocity of the incoming groups of particles become much larger than the velocity of the departing groups of particles.

The simple model of an arrival rate limited to twice the normal flux is not valid at conditions where the arriving particles are predominantly ions, since an extremely heavy flux of ions would tend to constrain the perpendicular flux. In order to achieve the augmented flux of twice the normal rate it is also required that the energy content of the ions be substantially larger than the energy content of the atom group involved in the collisions so that the velocity of arriving particles be substantially greater than the normal unenhanced velocity. A high probability of collision is also required.

A test of the charge-exchange model is shown in Fig. 10. An electron current was calculated on the basis of a work function predicted by the enhanced particle arrival rate. This was compared to the electron current measured, which was the observed net current minus the estimated ion current. The close agreement is obvious.

The relation used for the ion current is that presented in Fig. 7 although charge exchange was assumed. The use of this approximation is allowed since the directed energy of the incoming particles is conserved. The simple twofold enhancement of particle flux was used for the range of emitter temperatures and spacings since the ion current density, energy, and charge exchange probability were sufficient to induce a velocity of the atoms significantly higher than the normal thermal velocities. The normal arrival rates were based on an expression that related particle flux to spacing through the use of conventional Knudsen flow and continuum flow relations.

The explanation of increased electron emission by augmented arrival rate - work function depression through an ion current - charge-exchange process appears to be reasonable at the conditions tested. It should be noted that although the postulated mechanism might apply at lower ion currents and lower applied potentials, the simple twofold augmentation must be reduced to account for the reduced current density and energy of the incoming ion. Similar alterations are required at higher ion current densities where the enhancement of particle arrival rate can exceed the factor of two due to particle trapping.

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Concluding Remarks

It has been shown that the basic experimental observations of work functions of the cesium-tungsten system can be extrapolated to the conditions of operation of a practical thermionic converter. Some of the problems experienced heretofore in establishing this comparison may have been related to leakage currents, electron scattering, and space-charge effects. It is also postulated that the enhanced electron emission in the ignited mode can be related to the simple basic experiments if the arrival rate of cesium particles to the emitter is adjusted by recognizing an "ion pumping" by the process of charge exchange.

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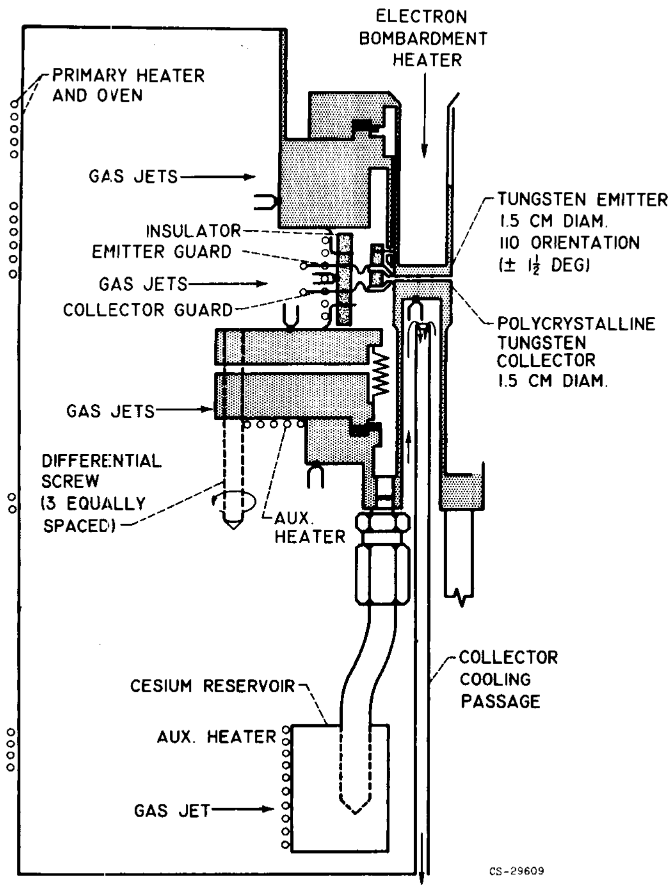

Figure 1. - Thermionic converter.

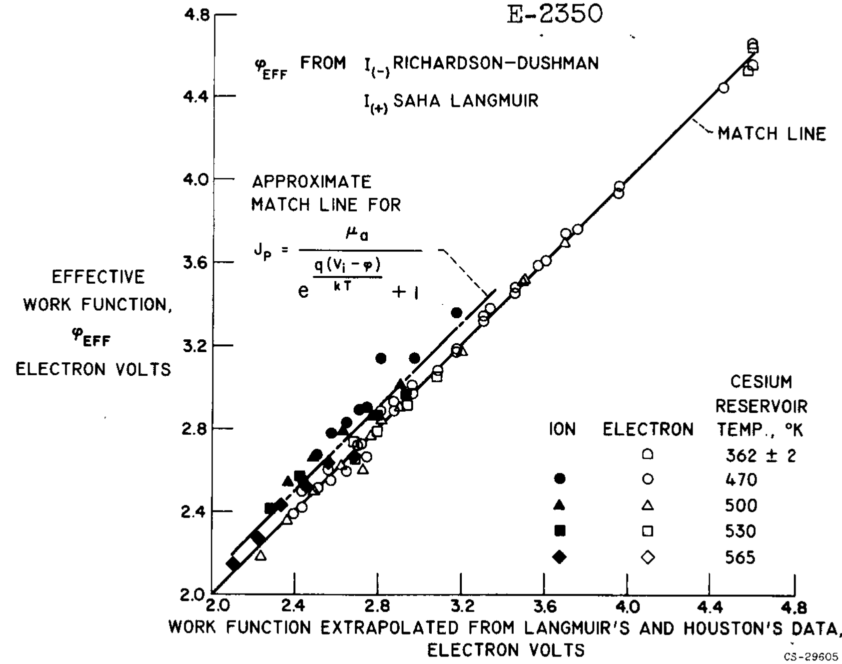

Figure 3. - Comparison of diode work functions based on ion and electron emission to values based on reference 1 and 2.

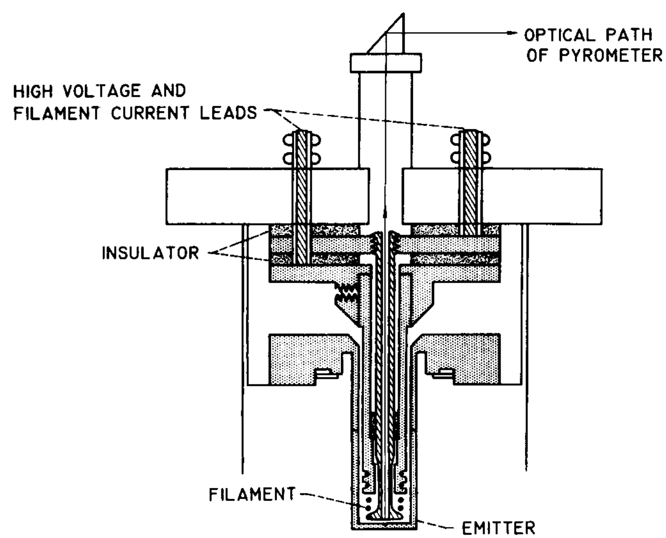

Figure 2. - Electron bombardment heater.

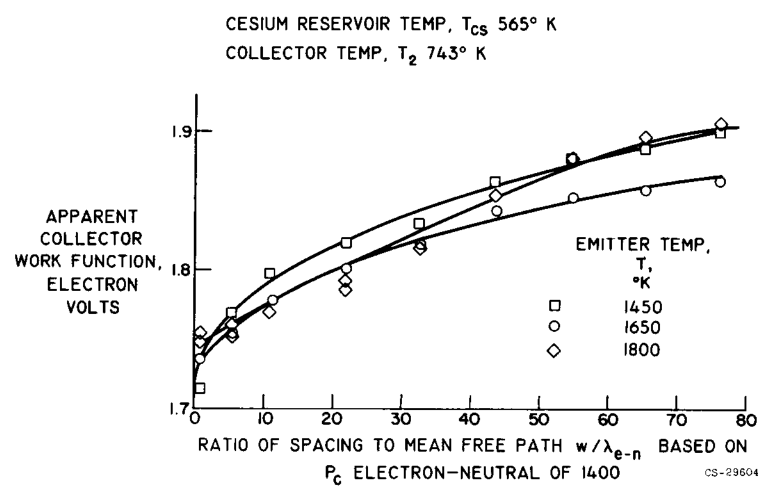

Figure 4. - Effect of electron scattering on apparent collector work function.

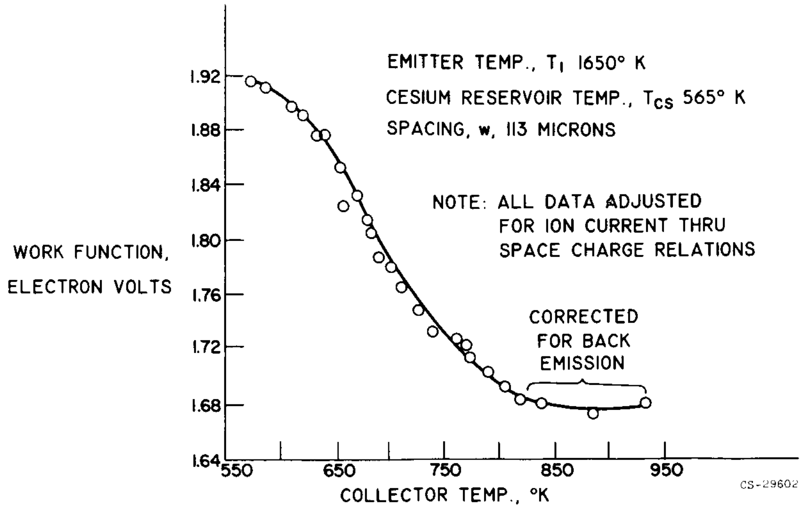

Figure 5. - Effect of temperature on apparent collector work function.

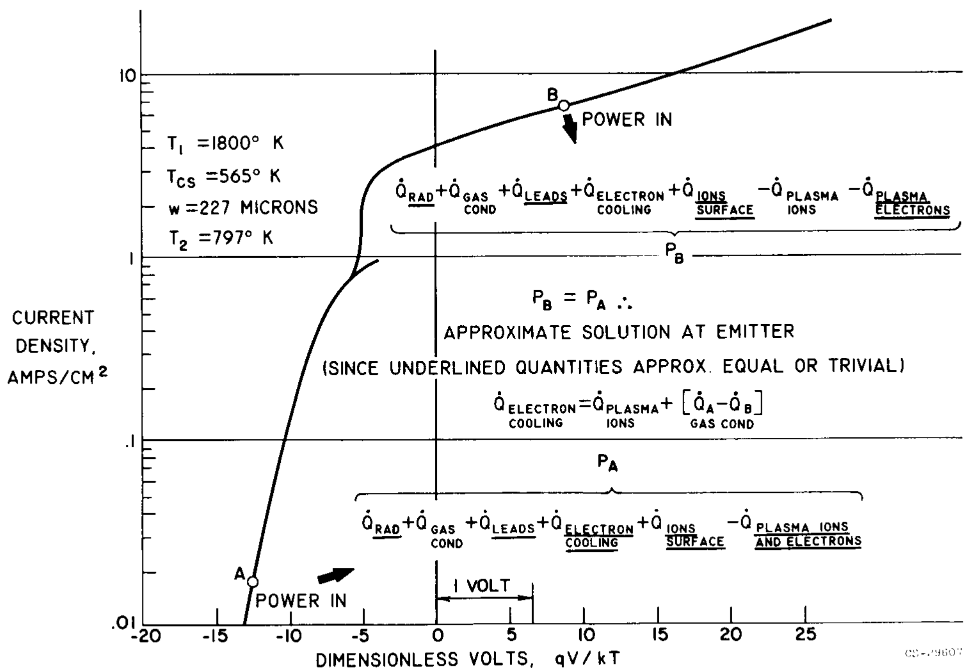

Figure 6. - Condition of balanced input power and emitter temperature.

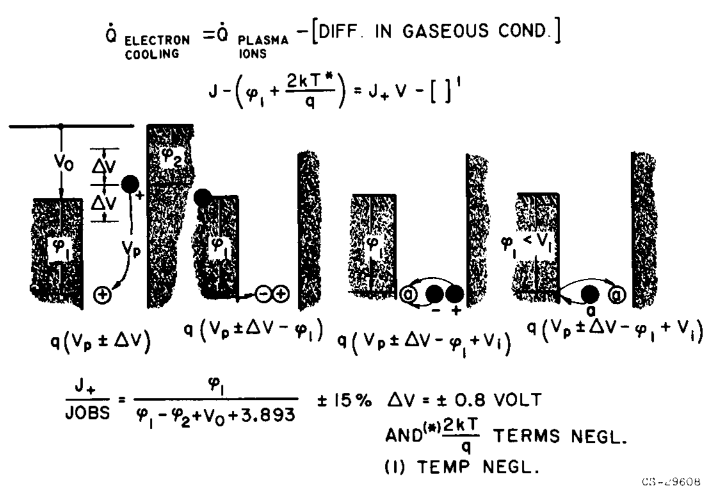

Figure 7. - Approximate relations used in estimating ion current.

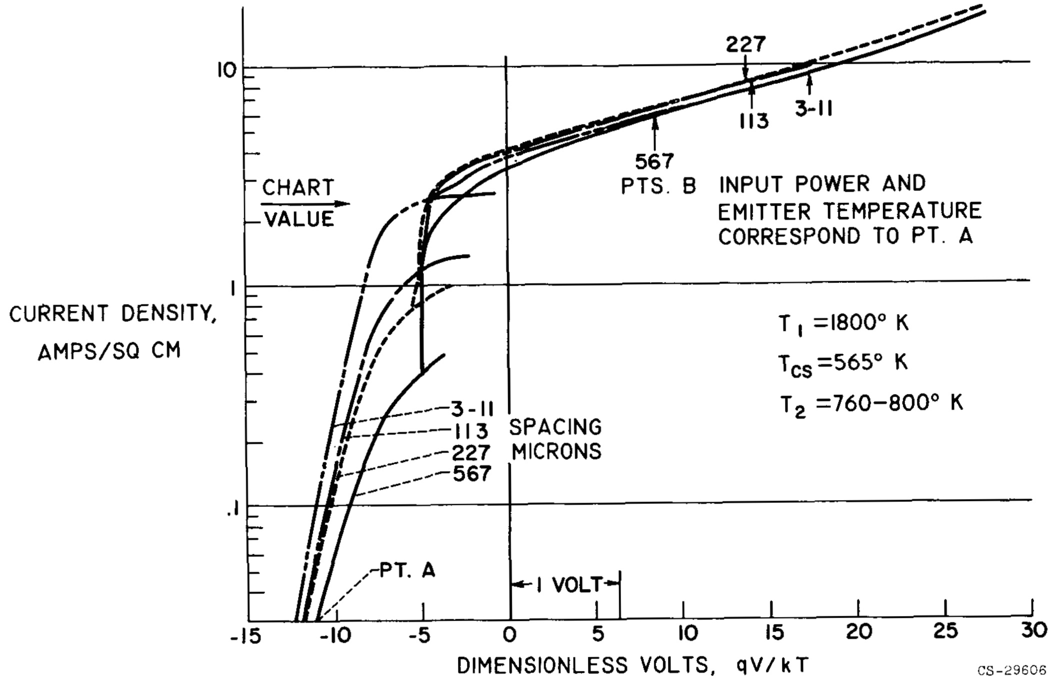

Figure 8. - Typical current-voltage curves and balanced inlet power - temperature points.

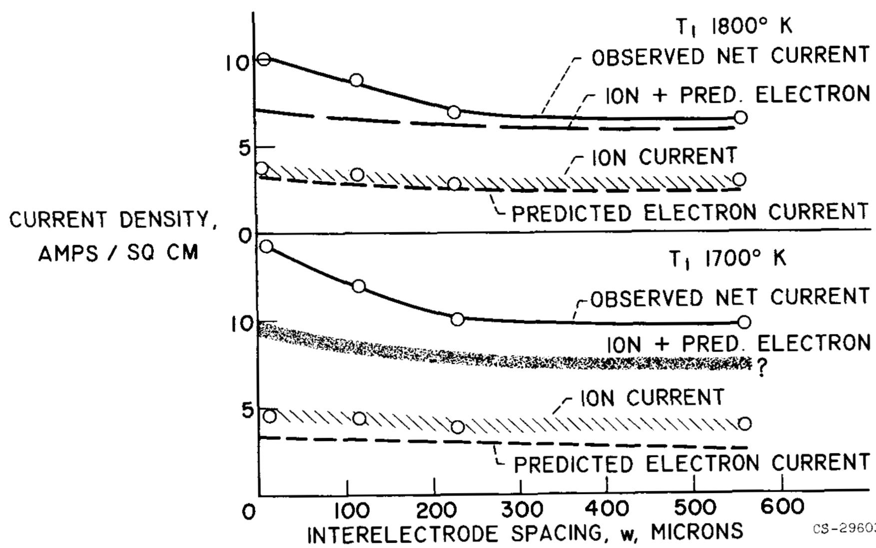

Figure 9. - Current distribution at balance point, cesium reservoir temperature, 565°K.

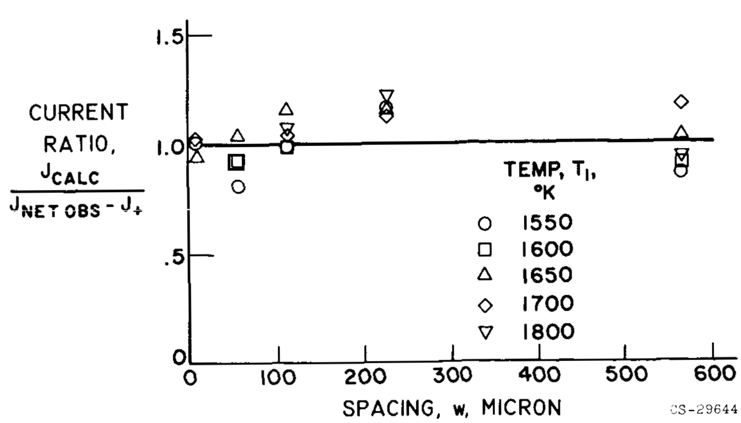

Figure 10. - Comparison of calculated electron current to observed electron current.

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